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CALIBRATION OF RELATIVE POSITION ERRORS OF THE RANGE CAPABLE DATA LINK AND LORAN-C

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The results of the preliminary calibration tests of the testbed system and Loran-C equipment to be used in the flight tests of the Electronic Grid Integration Program are reported. These ground and airborne tests were conducted to obtain data on basic system characteristics of Loran-C and the TDMA data link ground system needed for the construction of a realistic simulation to be used in testing the Kalman filter navigation algorithm under development for a combination data link/navigation program and for use in performance analysis of the live flight tests of that program.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

OBJECTIVE

The Electronic Grid Integration Program is an analytical and experimental effort to develop and evaluate techniques for achieving improved relative position registration between tactical elements that use different navigation systems through exploitation of the inter-element range information inherent in the operation of a time division multiple access reporting and control data net linking them.

BACKGROUND

Efficient control of aircraft in modern tactical missions requires accurate and timely knowledge of aircraft position and status. The requirements on capacity and timeliness can be adequately met only by automatic digital data link reporting of position and status information derived by direct automatic readout from the on-board navigation system(s). There are several navigation aid systems in use by various USAF aircraft which can serve as the sources for the position information. Though derived from different sources, the position information transmitted in the common data net must all be in a common reference coordinate system. In addition to the usual "internal" errors typical of the individual navigation systems and the errors in coordinate conversion, use of different source systems by different aircraft leads to increased relative position error because of registration errors between systems. For example, the position computed from two colocated Loran-C receivers or two colocated Omega receivers would be expected to agree but not necessarily to agree with the position computed from the other system.

If the elements using these diverse navigation systems are linked by a synchronous time division multiple access data net such as SEEK BUS in which each unit carries a synchronized clock, then each has available not only the reported position of other elements in the data net but also the ranges to those elements as represented by the time-of-arrival of the data link position report messages. The position reports and associated range measurements provide a means for improving the relative position registration. If enough of these reports are available, they constitute, in fact, a secondary navigation system. The techniques for combining this additional

navigation information with that from the primary on-board navigation systems in such a way as to improve relative position registration is the subject of study of this program.

The problem has two basic facets. First, there is the problem of determining the optimal manner of combination of a set of redundant dissimilar measurements to obtain the best estimate of the variables (position coordinates). Second, there is the problem of the control of the interaction or feedback which inevitably results when data net members reciprocally use each other as navigation sources.

TECHNIQUE DESCRIPTION

In order to participate in the time division data link, each terminal must synchronize a local clock to the data link time standard by observing the times-of-arrival of messages from other units already synchronized and participating in the net. These other units may be ground reference units at surveyed locations or they may be other aircraft. In either case, the position of the unit transmitting is contained in the data link message and is available to the receiving unit. If the local terminal position is known, data terminal synchronization is rather straightforward and requires the observation of signals from only one other data link source, the position information being used to remove the radio propagation delay. With no prior knowledge of position, it is possible to achieve synchronism by observation of signals from at least three sources. The computations necessary to this type of passive time determination and local clock synchronization are essentially identical to those used to determine position from such synchronized navigation systems as Omega, Loran, and Navigation Satellite Systems.

In an avionics system wherein the navigation instruments and the data link terminal have been interconnected for purposes of position reporting on the data link, the data link terminal may make use of the position information computed by the navigation system to aid in synchronization (as, for example, when the minimum three data link sources are not received) or the position computation and synchronization computations could be combined in an integrated navigation/ data link computer. The commonality of the algorithms for the two processes suggests that considerable computer space could be saved by such an integration and the similarity of the input data (times-of-arrival of either radio navigation aid signals or data link signals)

suggests the possibility of combination of the input data themselves in a "single pass" position/synchronization computation in a common Kalman filter processor. Signals from the navigation system could be used to aid data terminal synchronization and data link signals could be used to aid navigation. In order to do this directly with a single local clock, the data net must be synchronized to the navigation system.

PROGRAM OUTLINE

The Electronic Grid Integration Program was undertaken to develop and test this concept. Initial development and test of the navigation/synchronization algorithm was conducted in a computer simulation.

Briefly, the simulation accepts as inputs the positions of fixed elements and path specifications for moving elements. At each multiple of a specified time increment (cycle time) after startup, the program computes for each navigating element the true range to all other elements, adds a random variable and bias, and delivers these as measurements to a position computation routine. This routine reverses the process and performs the multilateration computations on the "measurements" to determine system time and own position for each simulated unit. Source positions used in this process are the "reported" or last computed position for those sources that are themselves navigating, not the true position used by the data generation section of the program. Finally, the computed time and position of each element are compared to the true time and position and error statistics are compiled. This simulation was used for initial development and test of the basic time and position computation algorithm and to explore the effects of various system errors, sensitivity to system geometry, and parameter values in the tracking program.

A real-time version of the time and position computation portion of the simulation was written for an IBM 4π airborne computer to demonstrate that such a program was feasible for an airborne computer and to verify that the techniques embodied in the position and time computation algorithm would, in fact, work with real inputs; i.e., verify the simulation results by showing that the simulations were repeatable in live flight tests. Once it is verified that the simulation results can be achieved with practical hardware and software, the simulation can be used to investigate systems involving larger numbers of users and greater geographical extent than available for live tests. In order realistically to simulate the effect

of mixing data from users of various primary navigation systems in the data link ranging scheme described above, it was necessary to determine the characteristics of the primary navigation data to be combined. This is the objective of the tests reported here.

SECTION II

TEST RESULTS

TEST OBJECTIVE

Loran-C was chosen as the navigation system for integration with the data link terminal in the live flight test and demonstration program. The initial series of tests reported in this paper was conducted to obtain data on Loran-C signal characteristics, receiver characteristics, and position accuracy in the testbed area. These data are to be used to derive realistic parameters for use in the simulation and as a basis for comparison with later flight tests when data from Loran-C will be combined with data link measurements in the combined synchronization/position computation program.

TESTBED DESCRIPTION

Figure 1 shows the geographic layout of the four ground sites in the synchronized data net. They are all at surveyed positions and within line-of-sight of each other. The master site at Bedford had, in addition to the data link terminal, a data recording facility to record all messages on the TDMA data net. In addition, the master site was provided with a Loran timing receiver which could be phase locked to the Loran-C master signal and provided time reference pulses to the data link master terminal. Thus, the data link master timing source was slaved to the Loran-C time standard. The other three ground reference sites derived time from the data link signals of the data link master and were, therefore, indirectly slaved to Loran-C time standard. The ground data link sites were, in effect, made to be additional Loran-C slaves operating at the 970 MHz data link frequency.

The C-131 test aircraft was flown in the flight path shown in Figure 2. It was equipped with a data link terminal and a Teledyne Systems Company Loran-C receiver connected to deliver Loran time difference data and a synchronized GRI strobe to the data link terminal. The airborne terminal computer was programmed to compute once each second two independent positions; one from the Loran data and one from trilateration on data link signals. Both position reports were transmitted once per second on the data link and recorded at the Bedford ground terminal. Data on the relative position and timing accuracy obtainable in flight from the two systems independently was thus obtained.

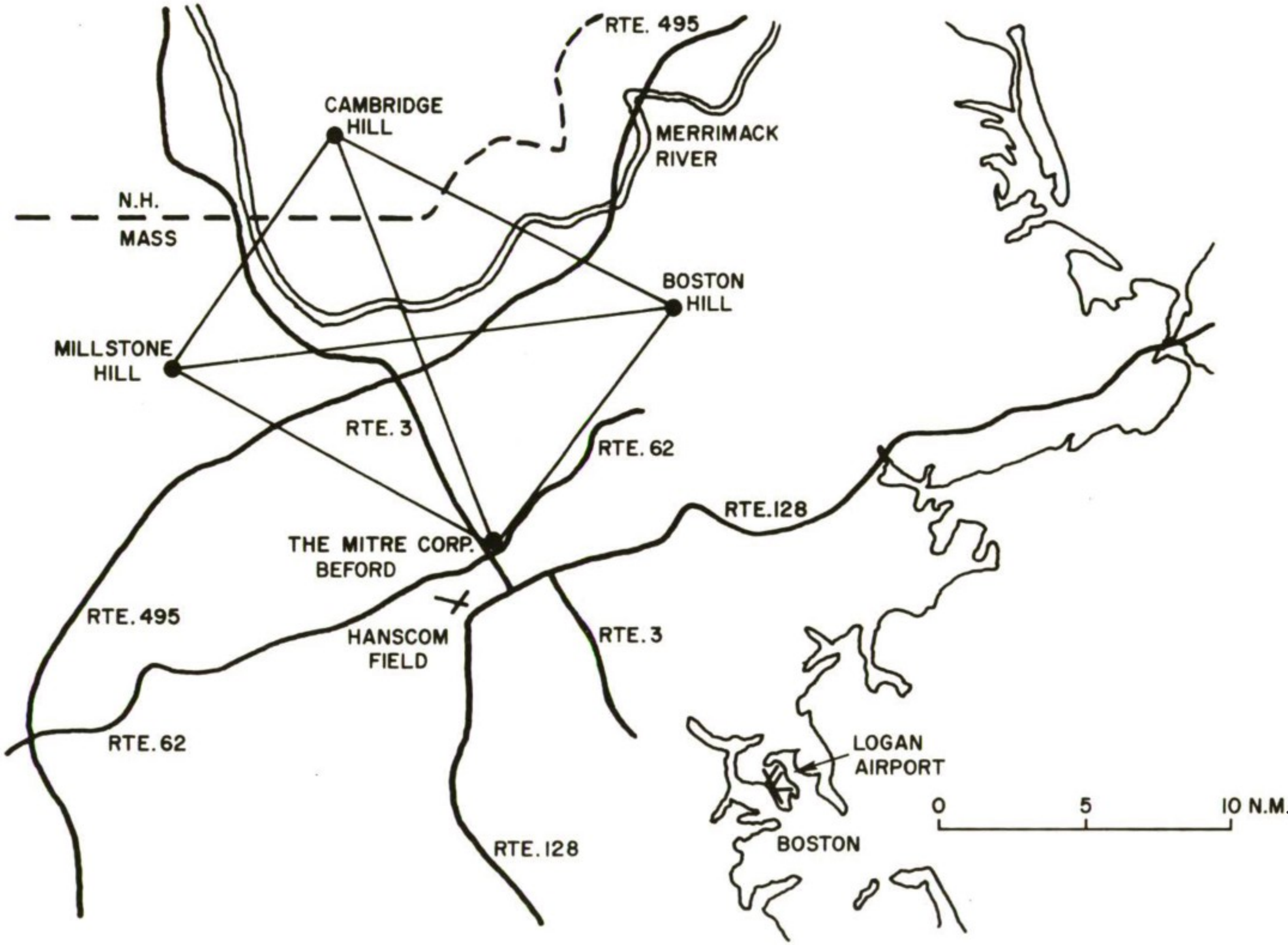

Figure 1 GROUND DATA LINK SYSTEM

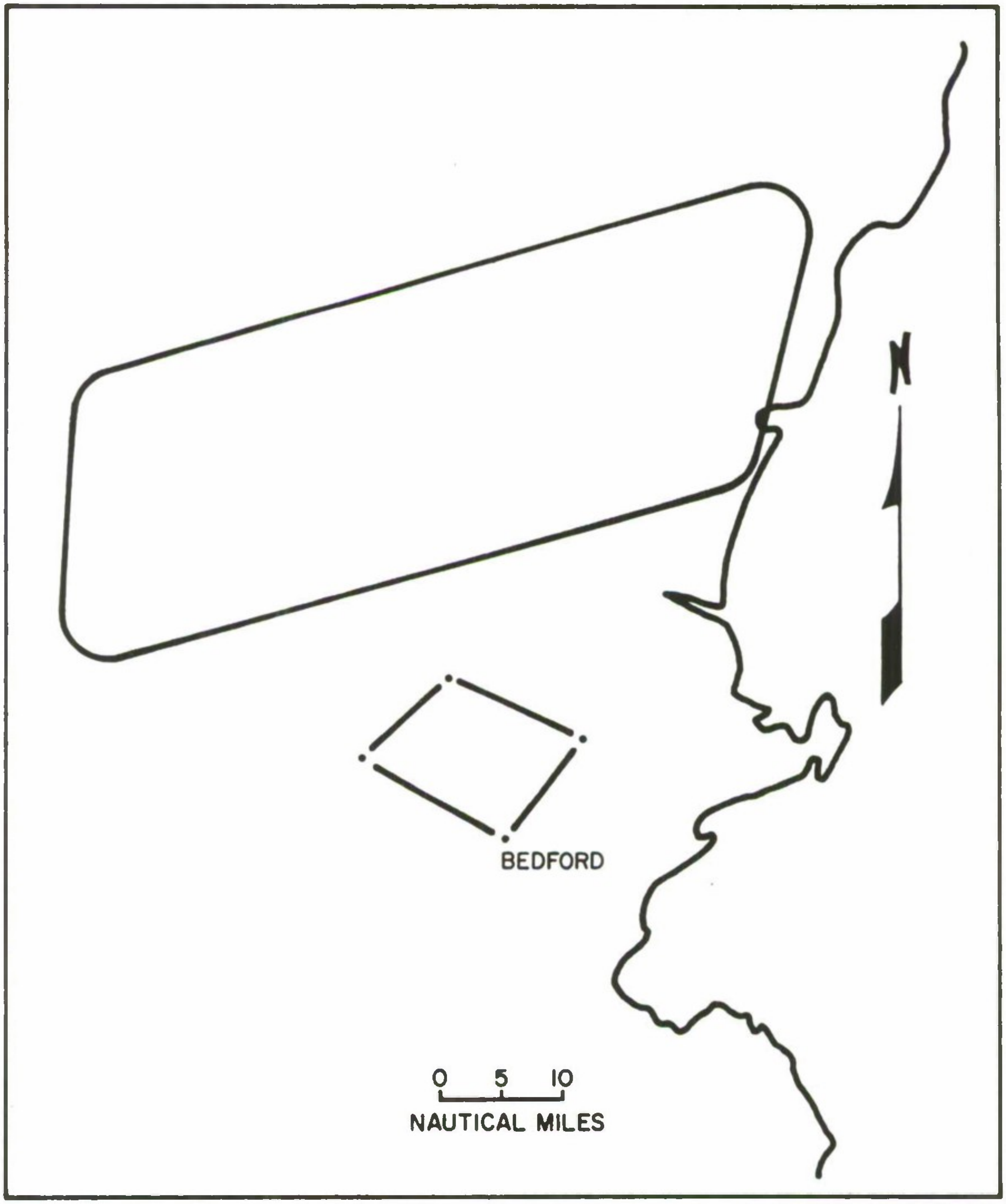

Figure 2 FLIGHT PLAN FOR CALIBRATION TESTS

The airborne terminal also transmitted a special "beacon" signal approximately once per second. Each of the four ground sites measured the time-of-arrival of this signal on the synchronized local clocks and transmitted these TOA data to Bedford for recording. The recorded times-of-arrival were then processed in a Post Mission Analysis Program (PMAP) to compute an independent estimate of aircraft true position. This position is independent of the time or position estimates made by the aircraft. Ground site synchronism was maintained to within 0.1 microsecond to produce a position accuracy of 100 to 200 feet.

LORAN-C CALIBRATION TESTS

Propagation and Position Bias

The Loran-C system operates at 100 kHz to provide stable ground wave signals at ranges up to 1000-1500 miles; therefore, when converting Loran signal arrival times to position, the propagation velocity of the ground wave signal must be used. The propagation velocity of ground waves is, however, path dependent because it is a function of earth surface conductivity. As an example, at a range of about 850 nautical miles, the difference between land and sea propagation time amounts to over 4 μsec. The paths from the testbed area to the East Coast Loran-C sites are inhomogeneous; i.e., mixed land and sea (see Figure 3). It is not practical to deal directly with such paths in computer programs for tactical airborne navigation.

In the computer program used in this exercise, the overland propagation velocity is used for all paths because all test flights were conducted over land and therefore all propagation path length changes were within the final overland portions of each path. The position bias that results from applying the overland velocity to the entire path containing appreciable sea surface was removed by adjustment of the emission delay correction for each slave. This was done simply by operating the Loran-C receiver and computer at a known fixed point (the Bedford site) and adjusting the emission delay corrections until the computer position matched the known position. This procedure obviously corrects for all errors, even local anomalies, at that one point. The correction will not necessarily be correct at other points in the area because of local anomalies, changes in the land/sea ratio in the paths from different locations within the test flight area, and changes in the secondary phase correction due to non-linearity near the source. This last effect is negligible at ranges greater than about 300 nautical miles and is frequently ignored in Loran-C navigation computer programs. It is mentioned here

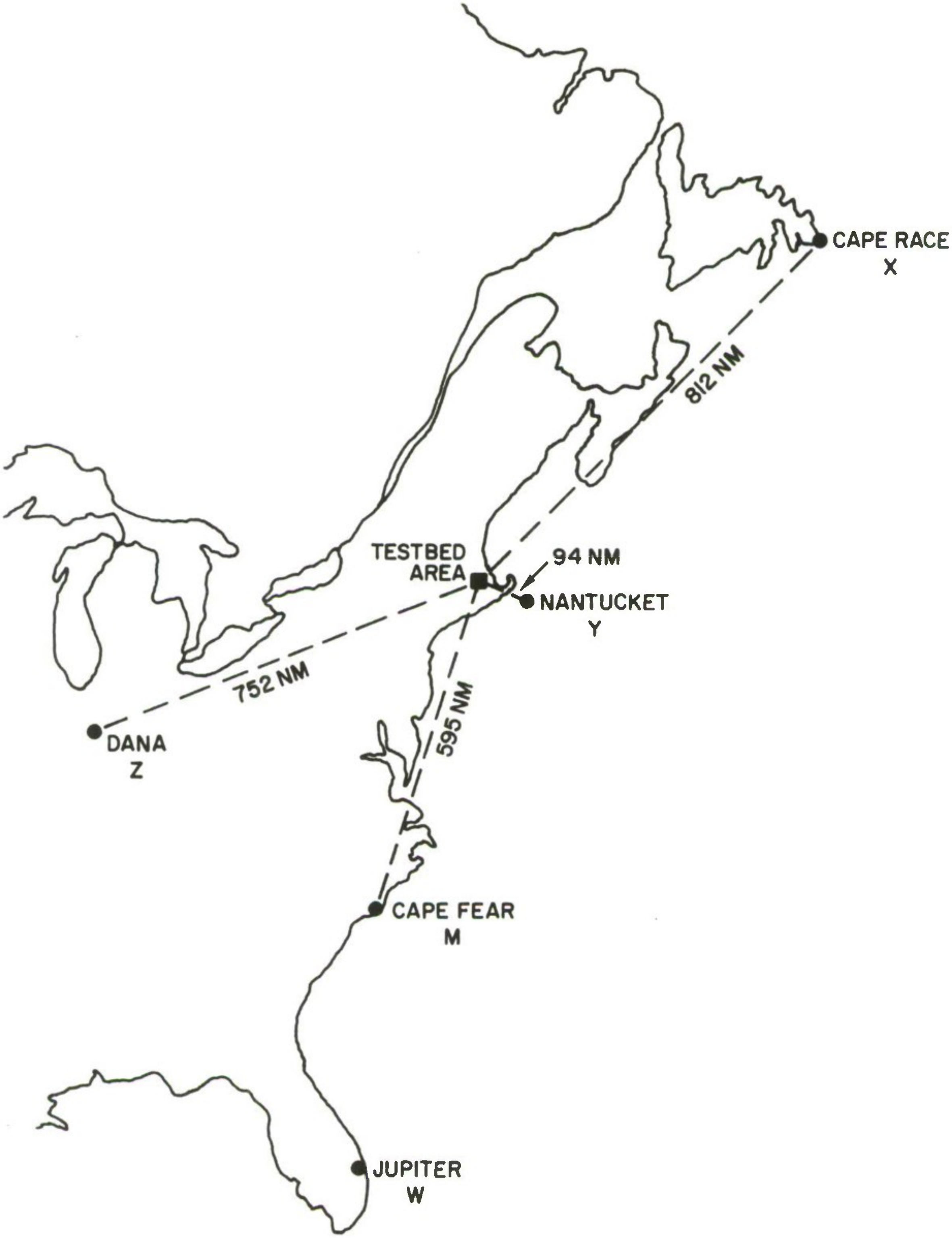

Figure 3 EAST COAST LORAN C CHAIN

because the Nantucket slave is only some 94 nautical miles from Bedford and this introduces another factor to be recognized when analyzing test results involving Nantucket signals. It is another of the error sources not corrected by the airborne computer program. Nevertheless, calibration at a known point leaves only errors introduced by changes in paths rather than the total discrepancy between actual and assumed velocity integrated over the entire path. Figure 4 is a plot of some computed positions using uncorrected overland and oversea velocities and the uncorrected emission delays at the Bedford site. It is presented to indicate the magnitude of the resultant position errors and to show that no single assumed velocity will produce the correct position with all slave pairs when the paths to the slaves are different. Individual corrections must be applied to each. There are four slaves in the East Coast chain (see Table I), three of which produce usable ground wave signals in the testbed area. The Loran-C receiver tracks only the master and two slaves at any one time; thus three different pairings are available and produce the three positions shown. The lines joining the computed positions are segments of the hyperbolic line of position (LOP) of the common site in the pairings. For convenience in plotting, the latitudes and longitudes are relative to 42° 30'N and 71° 15'W.

Measurement Noise

In addition to time difference bias from propagation effects, there is considerable "noise" in the time difference outputs of the Loran-C receiver and this in turn results in "noise" in the computed position. The Loran-C receiver used in these tests was designed for use in high performance aircraft without external velocity aid to the phase lock servo loops and for this reason the loops are of relatively wide bandwidth. The amount of the resulting position noise was of interest in the design of the position smoothing and tracking functions and Kalman filter weighting factors of the airborne computer program. Figures 5 and 6 are scatter plots of approximately 600 points each collected over a ten-minute period. The points show the characteristic error ellipse pattern of the hyperbolic Loran-C position solution for two slave pairings chosen to illustrate receiver and signal characteristics and the geometry prevailing in the test area. In these and all following plots, the longitude reference is 75°W.

It should be noted that the patterns result from two signals (TDA and TDB) containing partially correlated noise of different signal-to-noise ratios. The resulting patterns are therefore distorted from the typical normalized error ellipses derived purely from consideration of the hyperbolic grid geometry as are often seen in

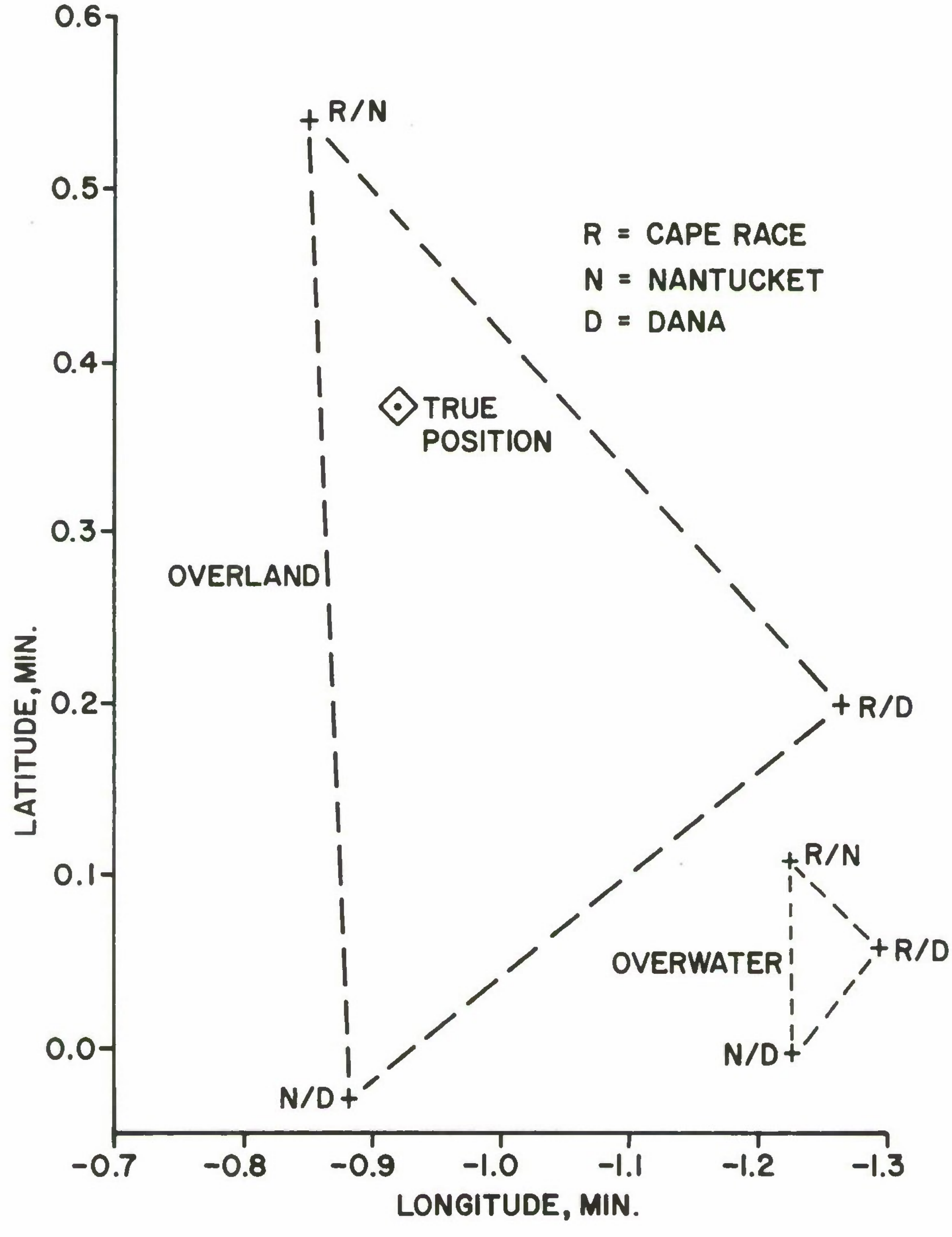

Figure 4 LORAN C POSITIONS DERIVED AT THE BEDFORD SITE

TABLE I

U.S. EAST COAST LORAN-C TRANSMITTERS

Group Repetition Rate SS7 (Period = 99,300 μsec.)

Designation	Location	Latitude	Longitude	Emission Delay, μs
M	Cape Fear, N.C.	34°03'46.36"N	77°54'46.19"W	0
W	Jupiter Inlet, Fla.	27°01'59.09"N	80°06'52.92"W	13,695.48
X	Cape Race, Nfld.	46°46'32.00"N	53°10'29.00"W	36,389.56
Y	Nantucket, Mass.	41°15'12.00"N	69°58'39.00"W	52,541.27
Z	Dana, Ind.	39°51'07.70"N	87°29'11.19"W	68,560.68

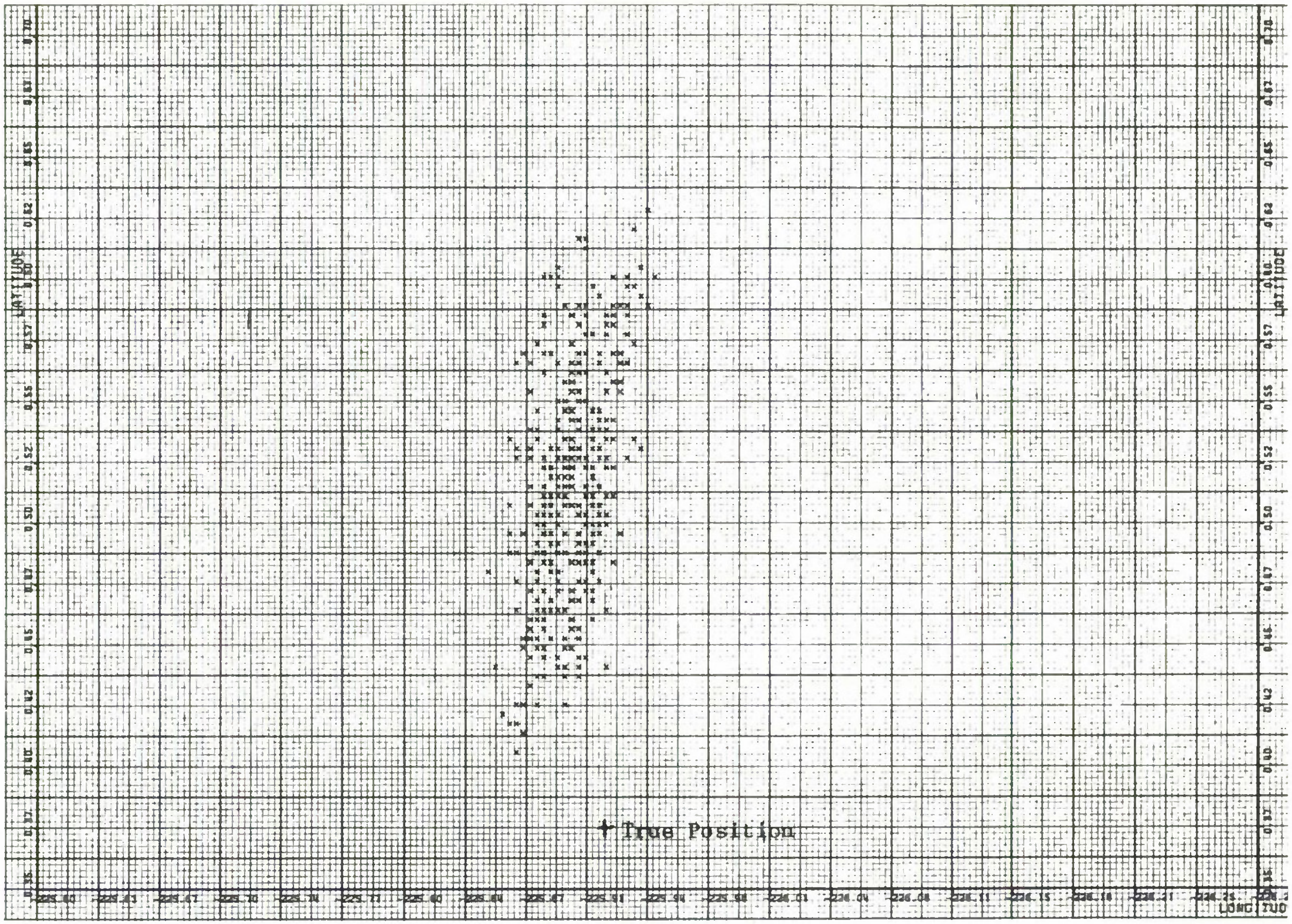

Figure 5 - Hyperbolic Loran-C Position Scatter Plot at Bedford Using Nantucket-Dana Slave Pair

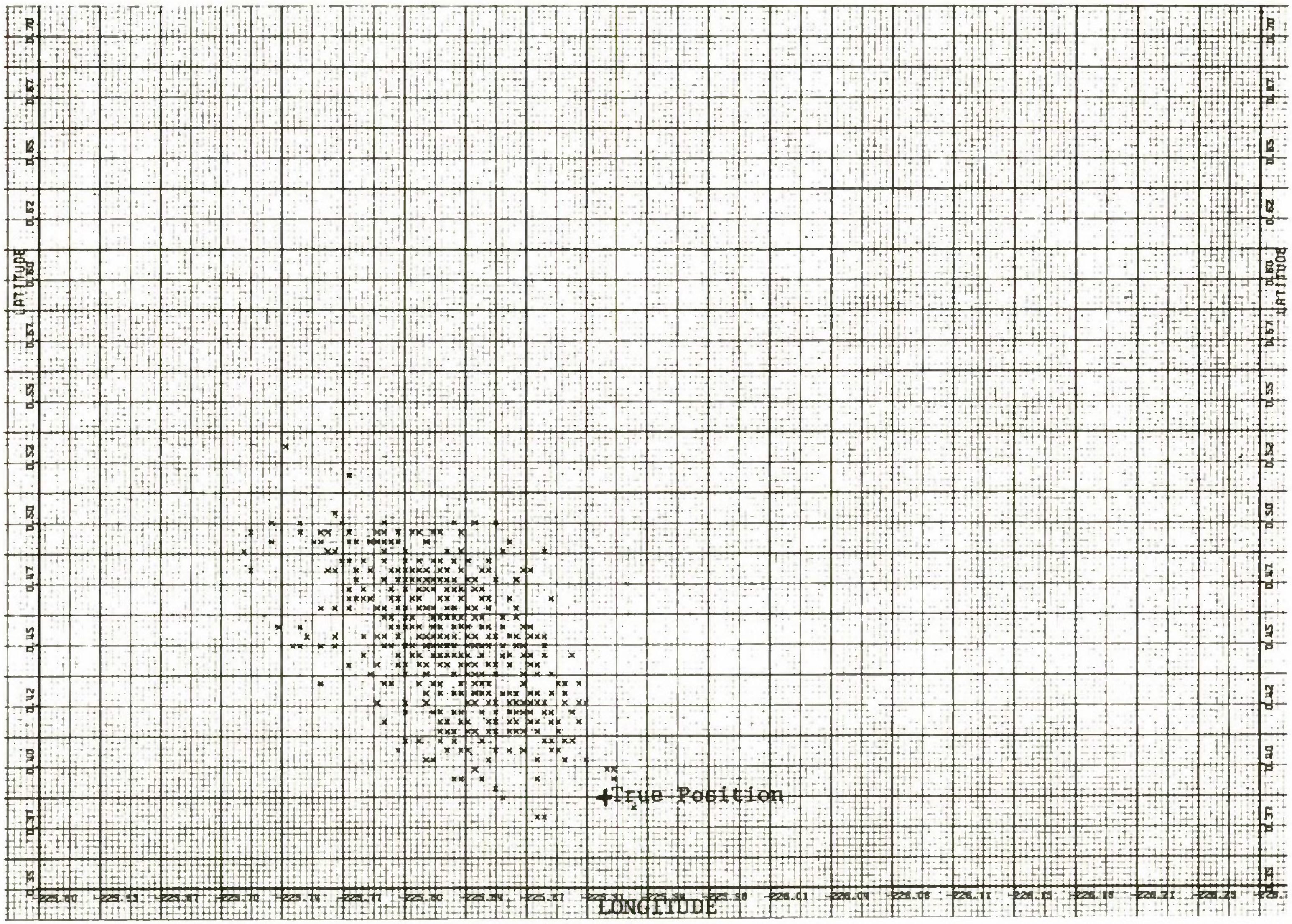

Figure 6 - Hyperbolic Loran-C Position Scatter Plot at Bedford Using Cape Race-Dana Slave Pair

the literature. The distributions as shown in Figures 5 and 6 are, however, representative of the actual error inputs for the entire test area as to shape and orientation. However, the magnitude of the signal-to-noise ratios may be different when airborne. The bias of the mean of the distributions from the true position of the Bedford site is a result of incomplete adjustment of emission delay correction at the time in the test when the data samples were recorded.

The positions plotted in Figures 5 and 6 were obtained by solving the usual hyperbolic equations employing only the two time difference values commonly used in Loran-C navigation systems. If, in addition, the time-of-arrival of the Loran-C master signal is known, a different type of solution may be employed. This technique, known as direct ranging Loran (DRL), is accomplished simply by processing the Loran-C data in the clock synchronization algorithm of the TDMA data link terminal computer. The resulting clock is synchronized to the Loran-C master and the position is then computed on the basis of three one-way pseudo-range measurements obtained from the time-of-arrival of the master and the two time differences. Figure 7 is a position scatter plot that results when the Loran-C data are processed in this DRL mode. Compare it to Figure 5 which is the hyperbolic data from the same slave pairing. No position smoothing was employed in Figures 5, 6, or 7.

The improvement in position computation geometry; i.e., the crossing angles of the circular lines of position as opposed to hyperbolic lines of position causes a reduction in sensitivity to measurement noise. This sensitivity factor is generally called the geometrical dilution of precision (GDOP). There is no improvement in bias errors; only a reduction in the variance about the biased mean. Note that the mean position in Figure 7 is essentially the same as in Figure 5. In this connection it is important to note that the improvement is realized only if clock correction estimates may be integrated or filtered with a time constant long compared to the lowest frequencies in the measurement noise spectrum. Any variation over time periods of the order of one time constant or greater will be observed as "varying bias". The practical upper limit for the filter time constant is set by the stability of the local time standard or oscillator (assuming that the time standard at the Loran-C transmitters is much more stable). Herein lies the key to the basic advantage of direct ranging over hyperbolation in reduction of position estimate variance.

Position estimate variance could be reduced equally by simply integrating or smoothing the position estimates themselves but in this case the limit is set by the maneuvers of the aircraft and in

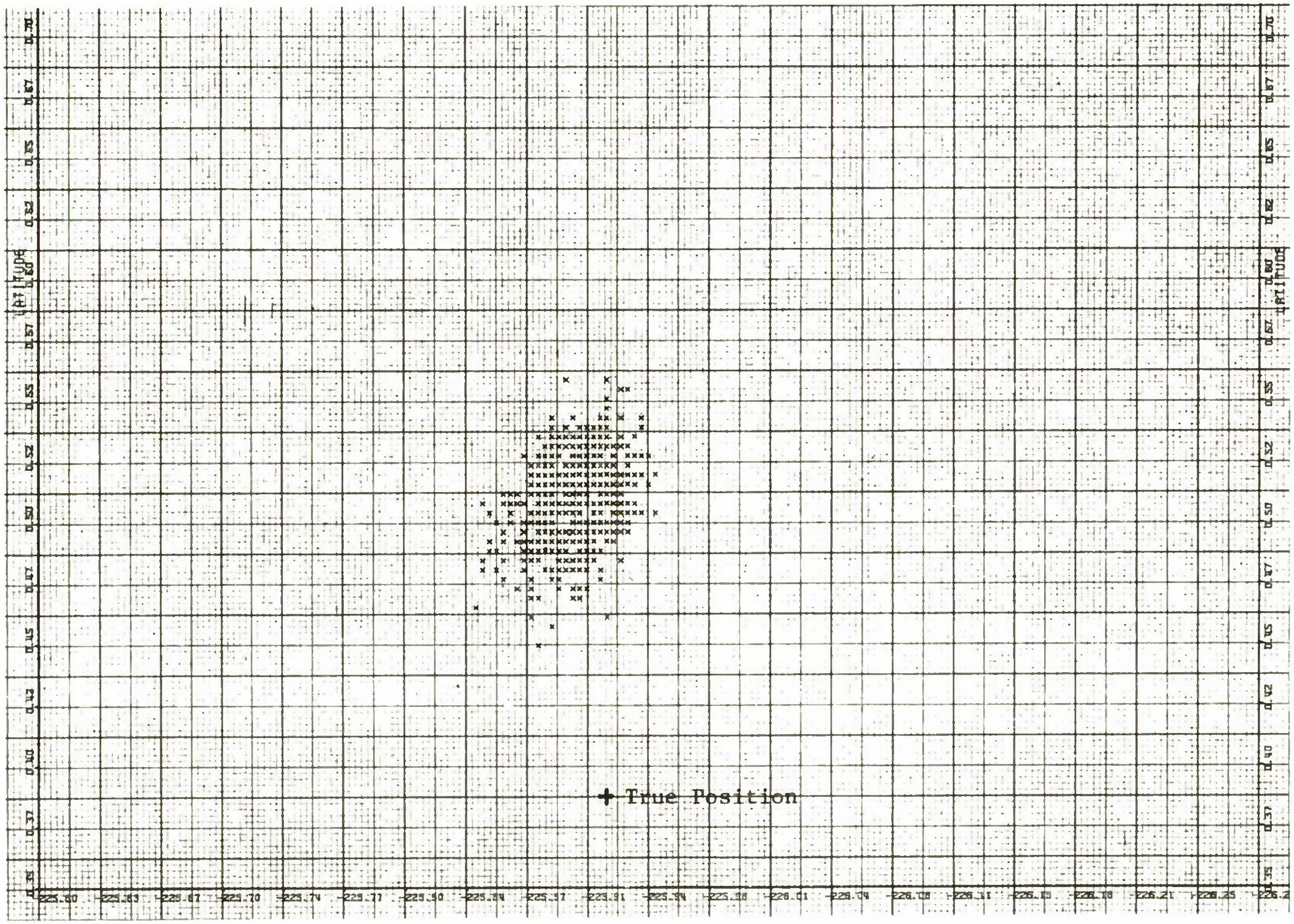

Figure 7 - Direct Ranging Loran-C Position Scatter Plot at Bedford Using Nantucket-Dana slave pair

general the unpredictable wanderings of the clock occur over much longer time spans than the spatial wanderings of the vehicle and, therefore, much heavier integration can be used. In other words, a straight line model may be applied to the clock much better than can a straight line model be applied to position. Heavy clock integration to reduce the GDOP followed by lighter integration of the position estimates themselves results in less variance than achievable by position estimate integration alone.

Another advantage of processing Loran-C data in a direct ranging mode is that once the local clock has been well synchronized, navigation may be accomplished in areas where only two usable signals are available for so long as the local clock may be trusted.

It might be well to point out here that if the vehicle is moving fast enough so that local variations in propagation cause variations in signal phase (time-of-arrival) at rates faster than the clock filter time constant, the effect of the local biases can also be reduced by the same reduction in GDOP. This is not, however, an unmixed blessing as it implies that the derived fix is dependent on vehicle speed and path and thus affects repeatability.

Figure 8 is a plot of latitude vs. time using the same data plotted in Figure 5. The essentially north-south orientation of the hyperbolic error ellipse for this slave pair causes that position noise subject to improvement by DRL to appear almost entirely in the latitude coordinate. It is apparent from this plot that the noise is by no means white. There are strong components with periods on the order of 50 to 100 seconds during this 400 second sample. If these variations are to be reduced by DRL, a time estimate filter with a time constant of 200 seconds or greater will be required.

Flight Test Results

Testbed Calibration Check

The flight tests covered in this report were conducted to obtain data on the relative position accuracy of Loran-C and the data link ranging and trilateration system over the flight paths to be used in the verification flights of the Kalman filter combination to be tested later in the program.

The first test was used to check the calibration of the testbed system itself. The airborne terminal was operated in a two-way ranging mode wherein the aircraft transmitted on the data link a ranging

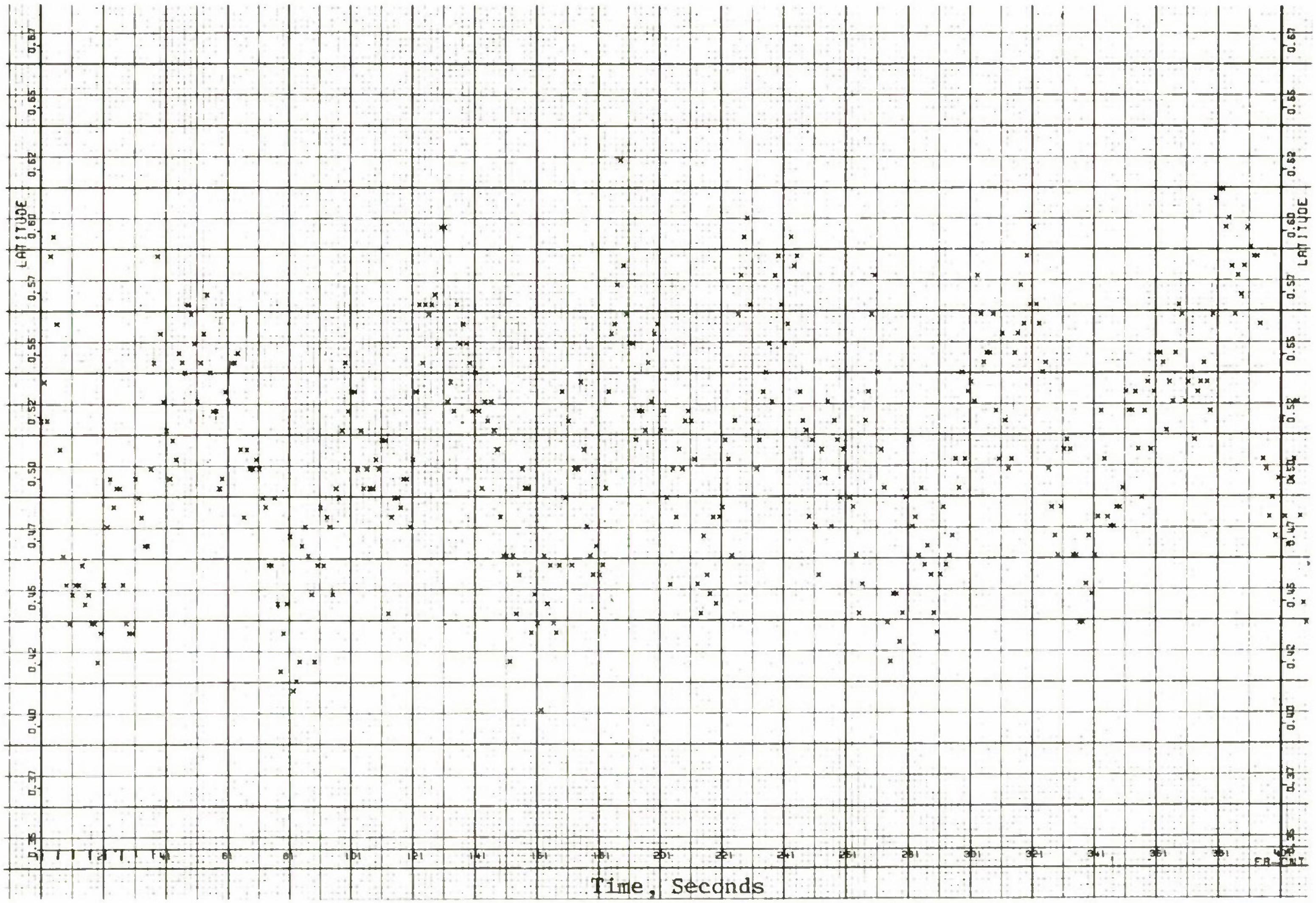

Figure 8 - Data From Figure 5 Replotted as Latitude vs Time to Show Low Frequency Variations

interrogation to which three of the ground sites replied. Collection of timing data on the round trip interrogation/reply set for each of the three replies allowed the airborne terminal to compute position by direct trilateration. The aircraft also emitted a special "beacon" message whose time-of-arrival was measured at each of the four ground sites. These time measurements were relayed to Bedford over the digital data link and recorded there on magnetic tape along with the position computed and reported by the aircraft. These time measurements were the inputs to the Post Mission Analysis Program (PMAP) which gave an independent position computation.

The position computed by the two-way ranging mode, as exercised by the aircraft, is independent of errors in synchronization of the ground data link terminals but is sensitive to uncertainty in equipment time delays in the three round trip signal paths. The PMAP position solution, on the other hand, is independent of errors in equipment delay other than those at the Bedford master station alone, but it is sensitive to synchronism errors in the ground system. By comparing simultaneous position solutions from the two systems an overall check on ground system calibration is obtained. Figure 9 is a sample plot from an early test. The bias shown in the blowup inset averaged 565 feet over the full eight-mile section in this region of good measurement geometry for both systems. Detailed analysis revealed an error in an extrapolation routine in the two-way ranging program in the aircraft which caused a 300 foot lag of reported position behind "true" position. Further search revealed a timing error at the Millstone Hill site which could have contributed up to 75 feet eastward bias to the ranging solution at this point. Correction of these errors and retest resulted in the performance shown in Figure 10 where the average bias is about 20 feet. PMAP solutions are unsmoothed while the ranging solution employs a smoothing factor of 0.25. In later tests the PMAP position which has now been calibrated against an active two-way ranging trilateration system will be used as the reference in comparing the performance of various modes of the Kalman filter Loran-C/TDMA navigation system.

Loran-C Calibration

The next tests in the calibration series were conducted to determine the relative accuracy of Loran-C and the TDMA passive one-way ranging positioning mode. Results over several flight path segments are presented in Figures 11 through 17. In all these tests the emission delay corrections required to calibrate to the Bedford Loran-C position were made in the airborne computer about 18-24 hours before the flight.

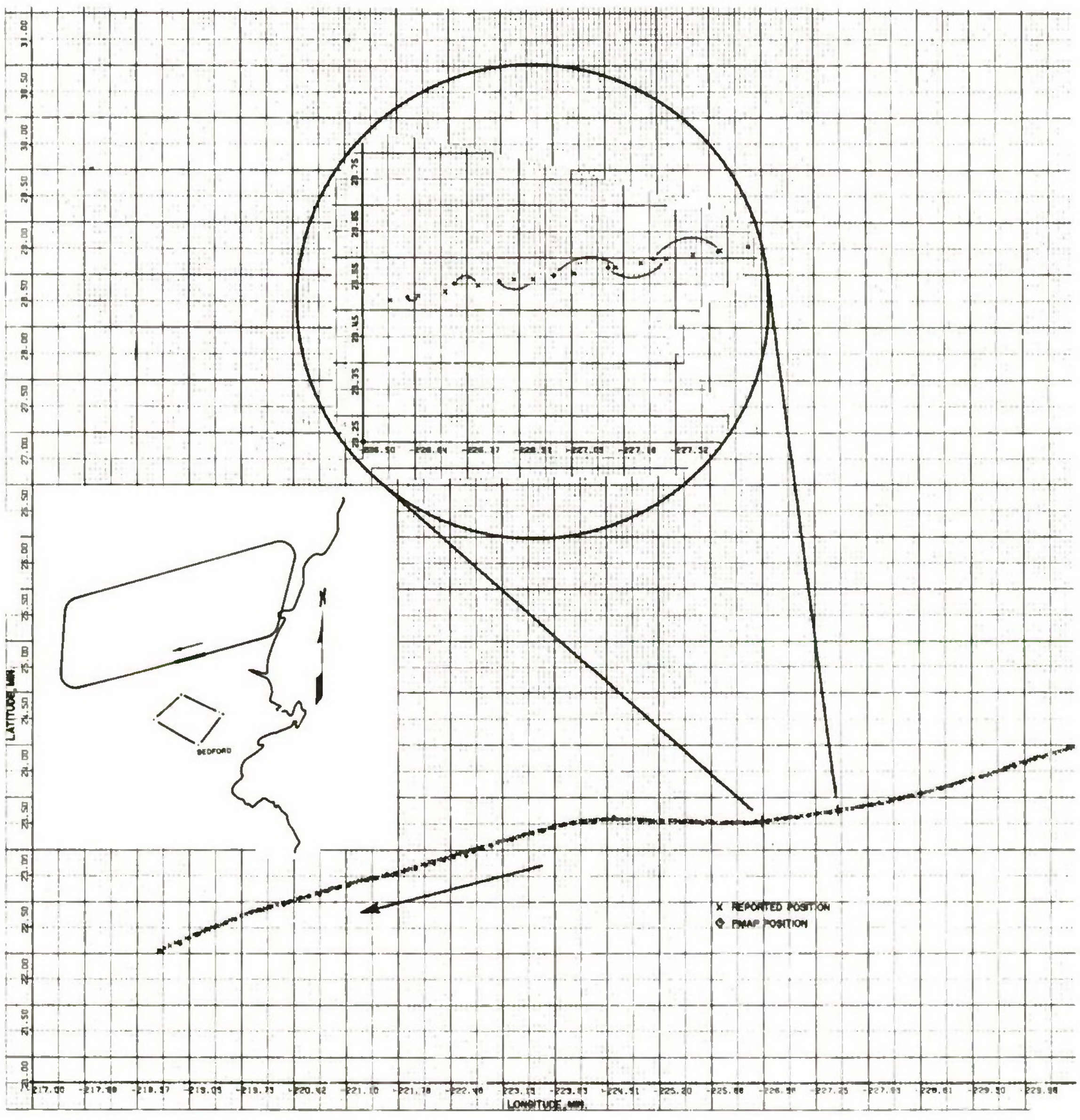

Figure 9 - Calibration of Post Mission Analysis Program, Run 1

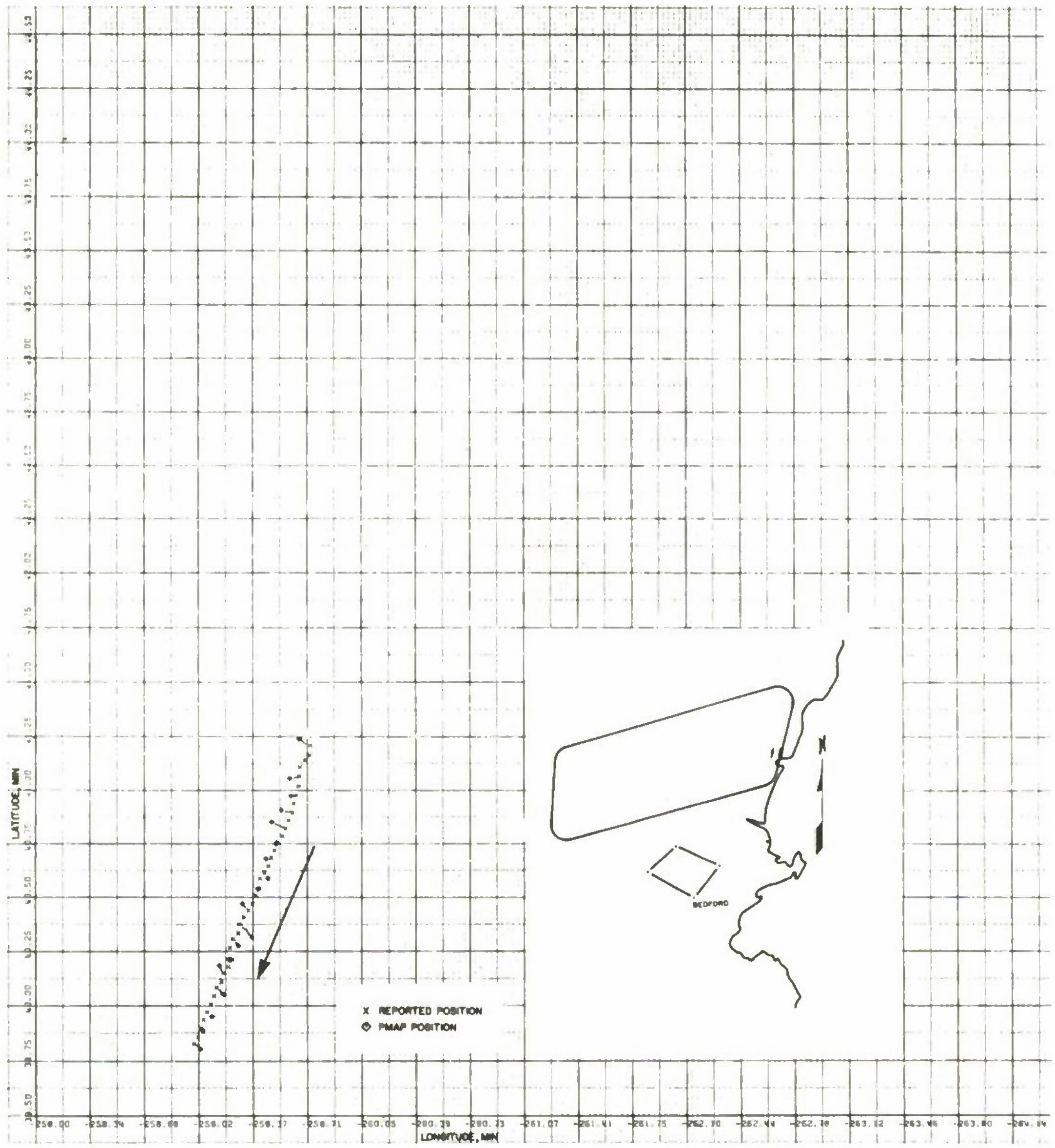

Figure 10 - Calibration of Post Mission Analysis Program, Run 2

Figure 11 shows a plot of a flight segment during which the airborne terminal computed and reported two independent positions - one based on hyperbolic Loran-C using Cape Race and Nantucket as the slave pair and one based on passive (one-way) ranging on the signals of the four synchronized ground data link terminals. The maximum separation between the two tracks is about 400 feet with the track derived from data link having an average southward bias of about 200 feet relative to Loran-C. Figure 12 is a similar plot for a flight segment 22 miles north of that in Figure 11. Overall, the picture is much the same as in Figure 11. Maximum separation is again about 400 feet this time with a small southeastward net bias in the Loran-C position. The indication of these plots is that the emission delay corrections determined at the Bedford Site to calibrate Loran-C position to the testbed grid position at that point hold reasonably well over the area to within the repeatable accuracy of Loran-C as shown in the scatter plots.

But now we turn to Figures 13, 14, and 15. These segments are from a flight in which Nantucket and Dana were selected as the Loran-C slave pair. Comparing Figures 13 and 11, the Loran-C track is now noticeably more unstable and there is considerable bias between the two tracks with both biased relative to the PMAP position. The increase in the random deviations of the Loran-C track is due to the fact that the North/South gradient of the Nantucket-Dana hyperbolic grid is 1340 feet/microsecond for Dana while the gradient of the Cape Race-Nantucket grid is 680 feet/microsecond for Cape Race. The variation in time differences from the two slaves is very nearly the same; however, the resulting position variations are about twice as great for Dana. The bias of the data link derived position from the PMAP position was later determined to have been caused by synchronization error in the data link transmitter at the Millstone Hill site. The data in Figure 14 were obtained approximately one hour later on the next orbit of the test aircraft as it passed through the same segment. The use of direct ranging Loran (DRL) during this pass has smoothed out some of the undulations in the Loran-C track while leaving the bias northward of the PMAP positions essentially unchanged.

Going now to Figure 15 we note a rather large increase in this northerly bias - from 1/8 N.M. to 5/8 N.M. Figure 16 is a segment of this same northern leg of the flight path at the eastern end (see inset). The bias has decreased to 3/8 N.M. This flight path was repeated on several occasions over a period of three months. The discrepancy is real, repeatable, and not attributable to any detectable equipment failure. It occurs only when Dana is one of the selected slaves. It is a clear demonstration of the errors that may be encountered in overland Loran-C. Study of field test data collected by others in several regions of the eastern U.S. revealed that

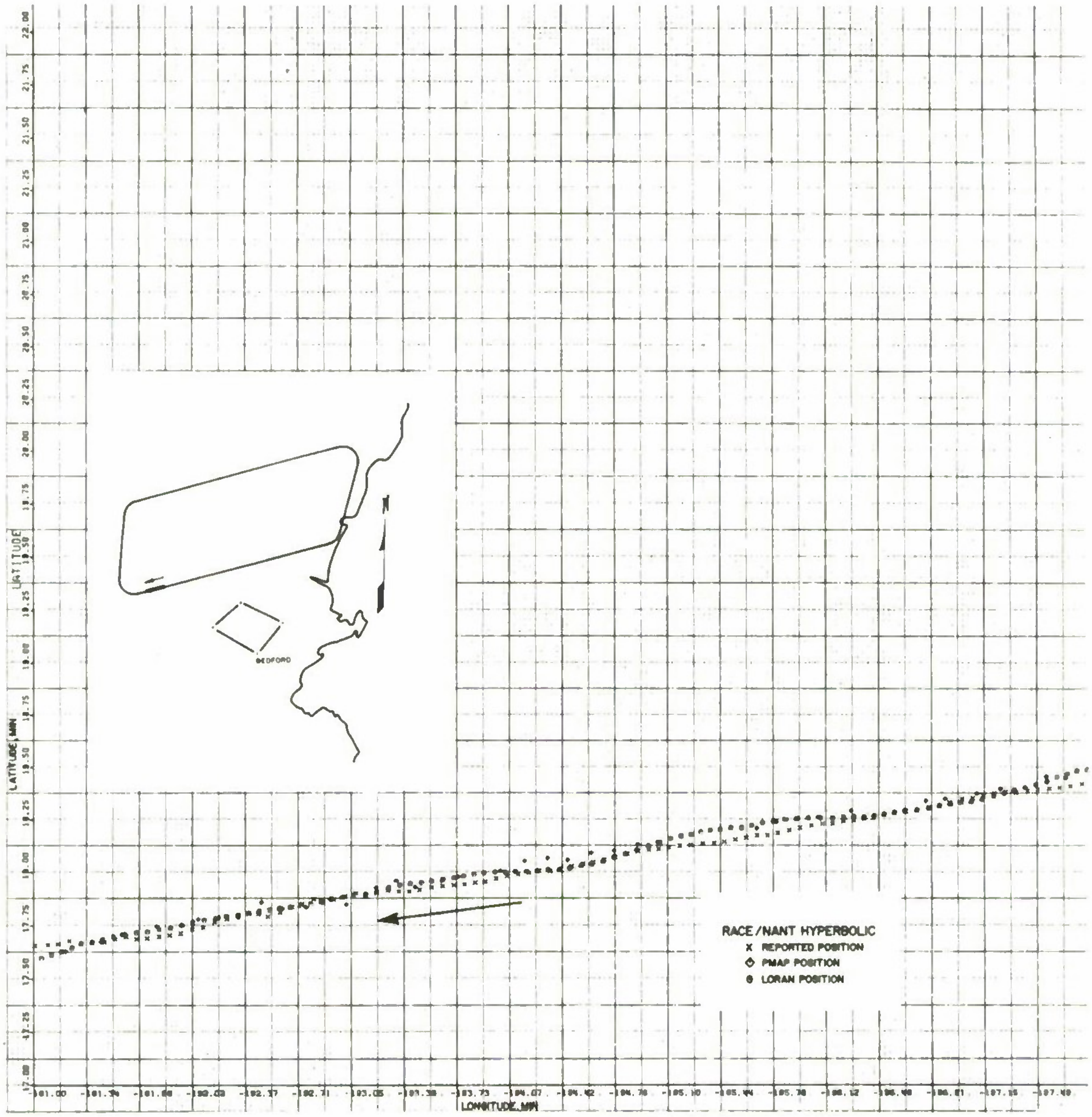

Figure 11 - Loran C registration-Cape Race and Nantucket, Southern Leg

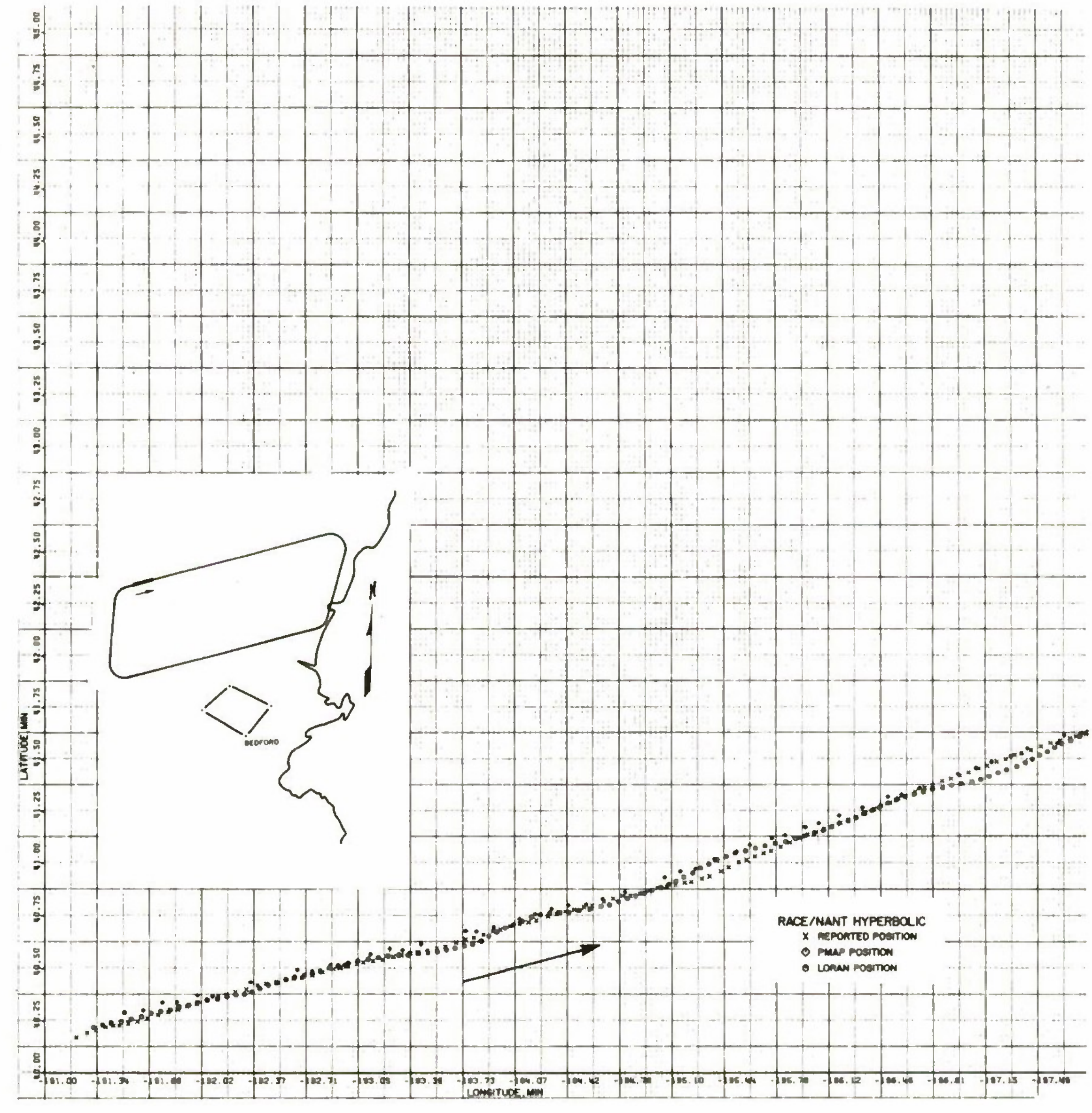

Figure 12 - Loran C Registration-Cape Race and Nantucket, Northern Leg

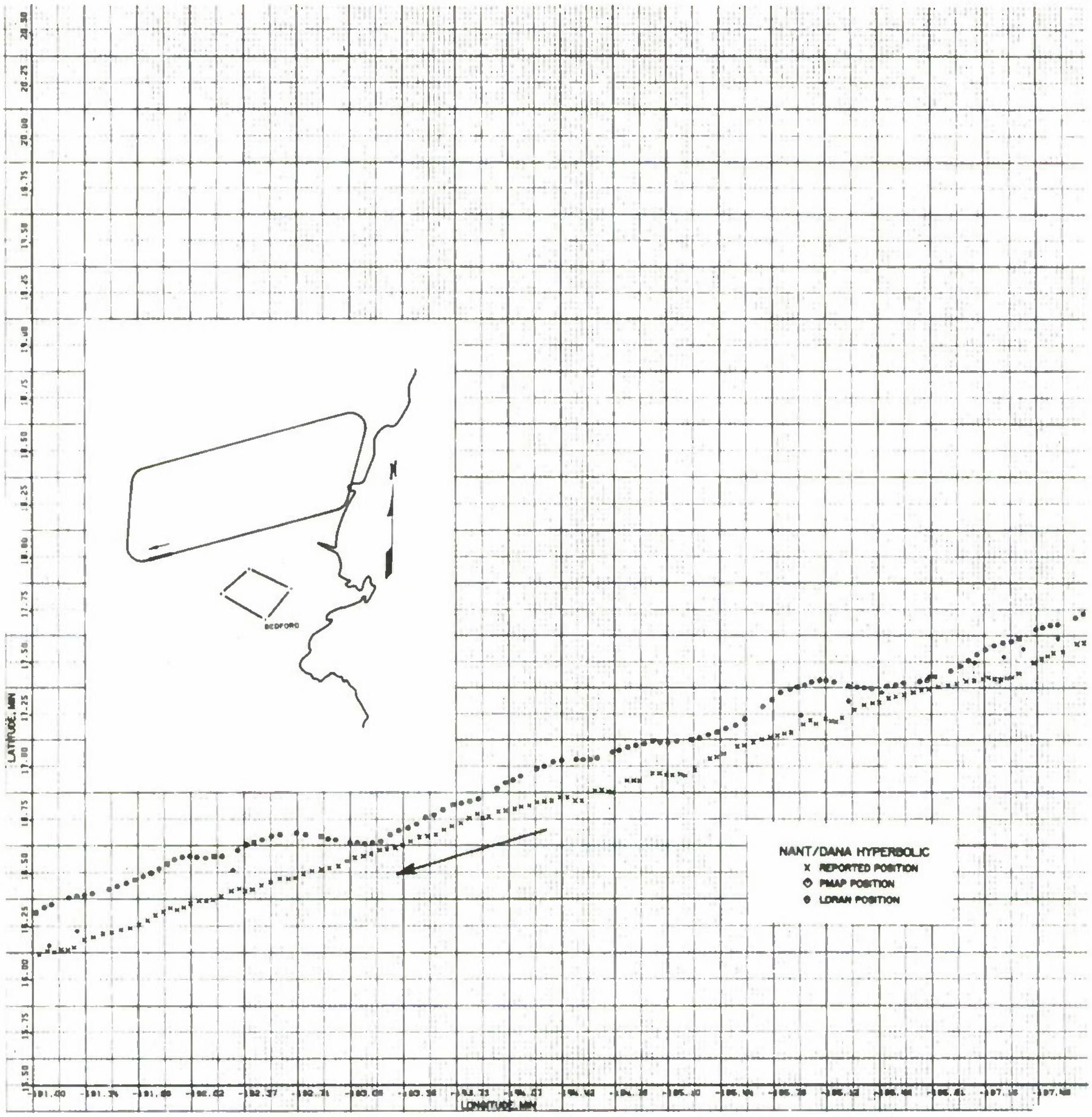

Figure 13 - Loran C Registration- Nantucket and Dana, Southern Leg

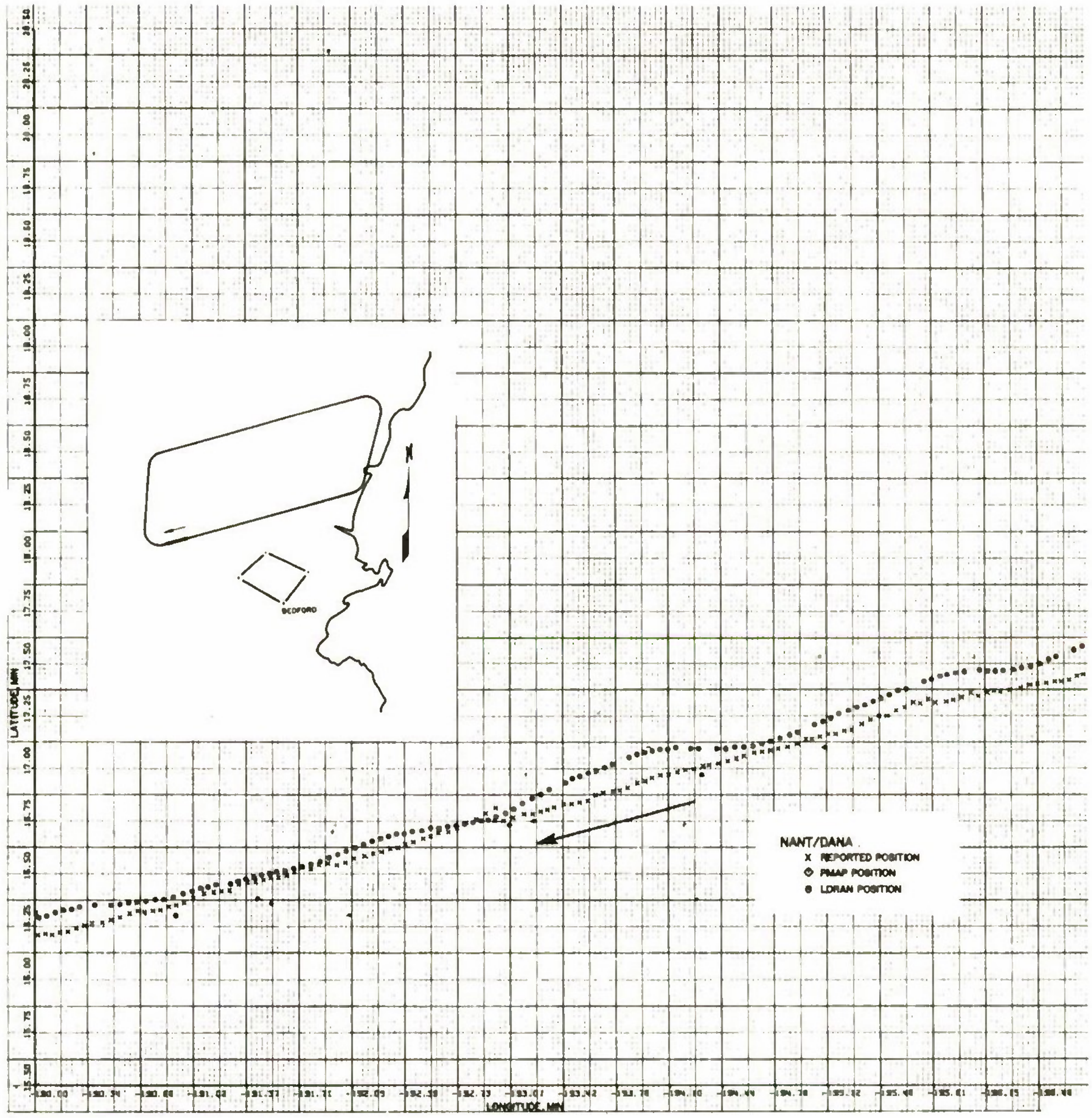

Figure 14 - Loran C Registration-Nantucket and Dana, Southern Leg, Direct Ranging Loran

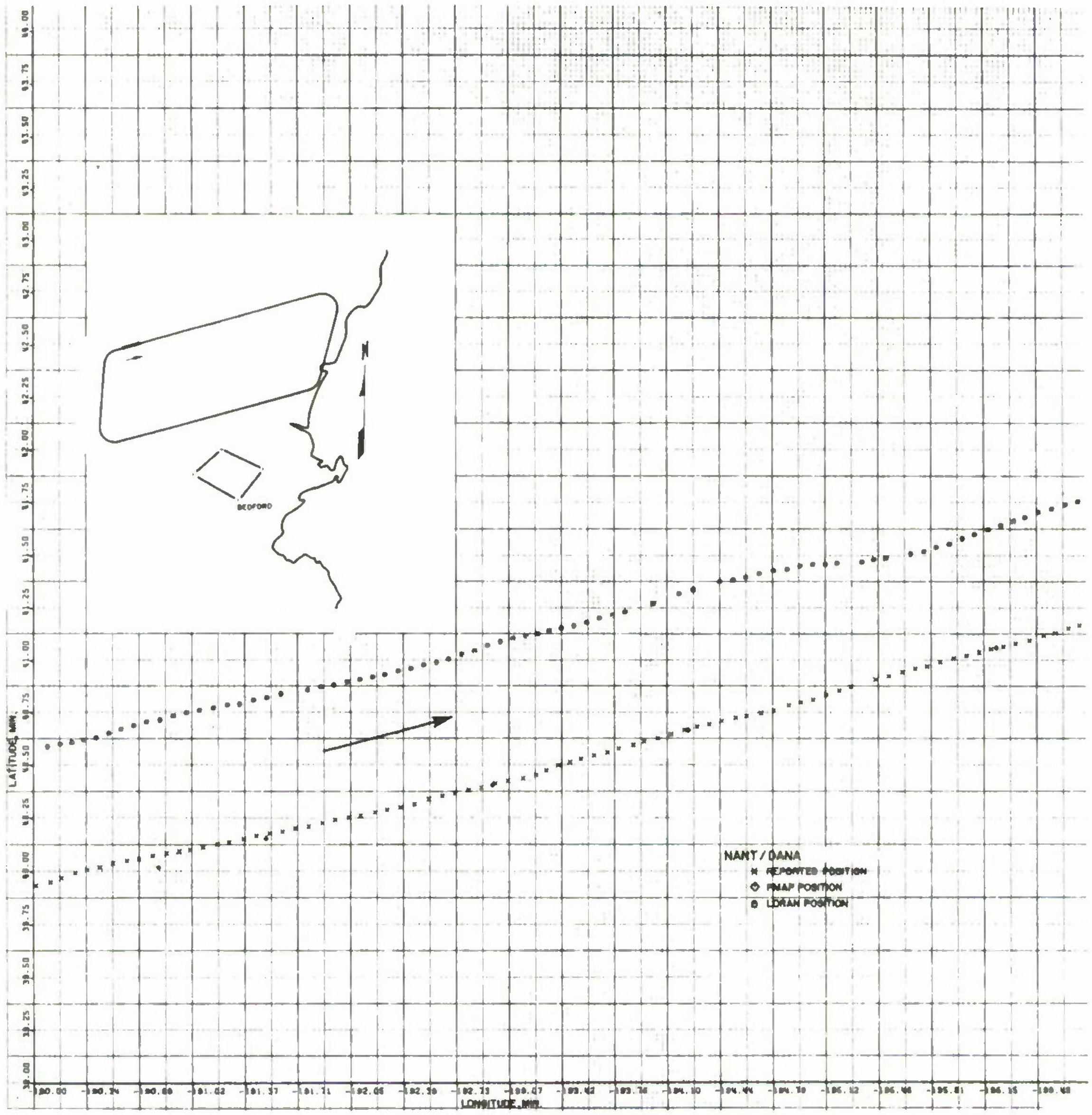

Figure 15 - Loran C Registration-Nantucket and Dana, Northern Leg,
Direct Ranging Loran

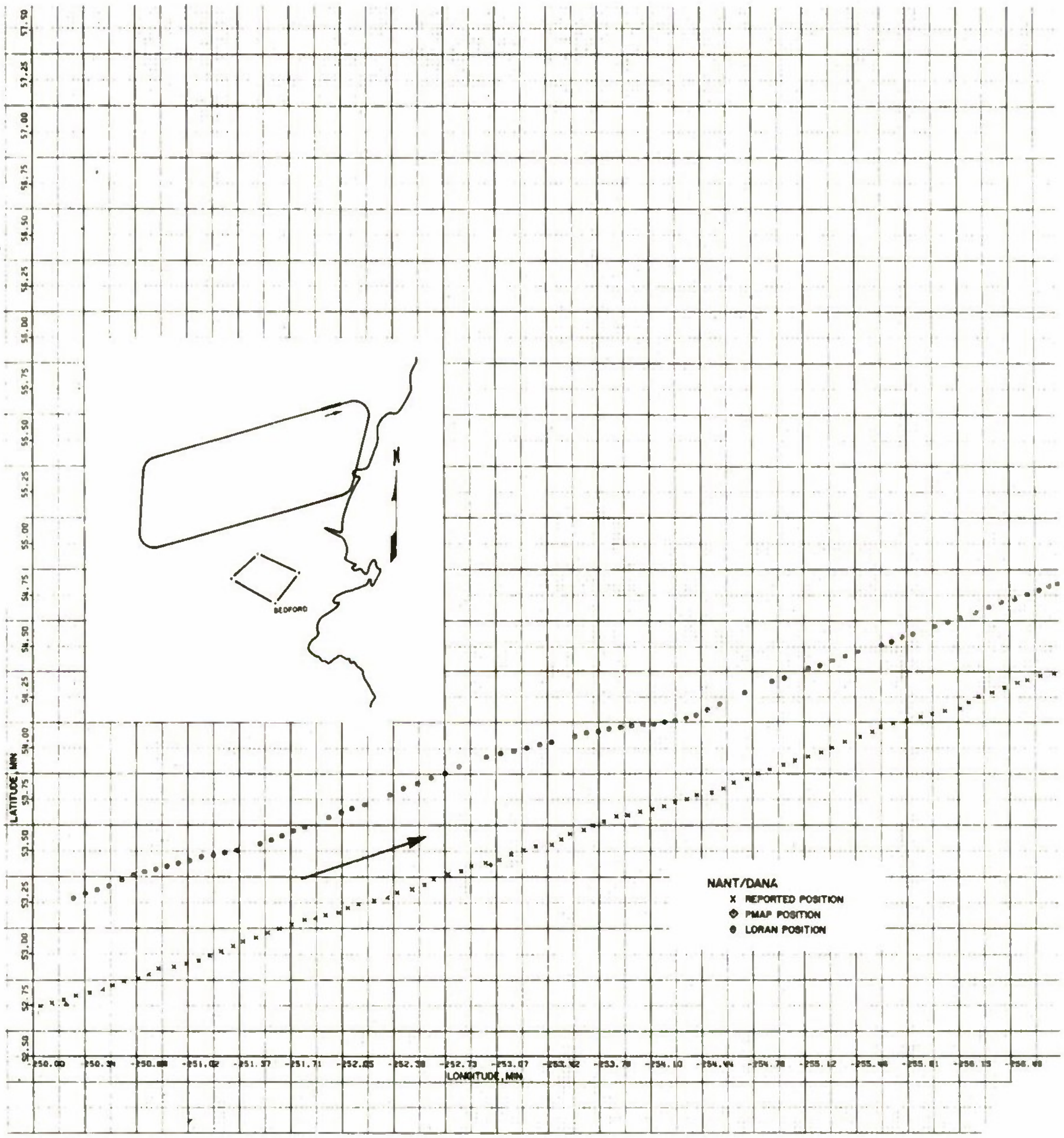

Figure 16 - Loran C Registration-Nantucket and Dana Northern Leg, Direct Ranging Loran

local grid warpage of this magnitude has been observed both in mountainous areas and in the vicinity of coastlines. We have both mountains and coastlines in this test area. It is interesting to note that the warp affects only the Dana signal. This selective effect has also been noted by other observers.

Figure 17 illustrates an entirely different type of track error that is attributable to false phase lock of the Loran-C receiver. Just prior to the beginning of the plot the receiver was correctly phase locked, then (apparently) the envelope-to-phase relationship of the Loran-C signal from Cape Race became such as to cause the envelope deriver in the Loran-C receiver to pull the phase-lock loop forward (earlier) to the next cycle in the pulse. This 10 microsecond decrease in time difference caused the abrupt jump of ≈ 1 1/8 N.M. followed one minute later by a return to the correct cycle. Careful adjustment of envelope deriver circuits is necessary if this is to be avoided in areas of pulse distortion.

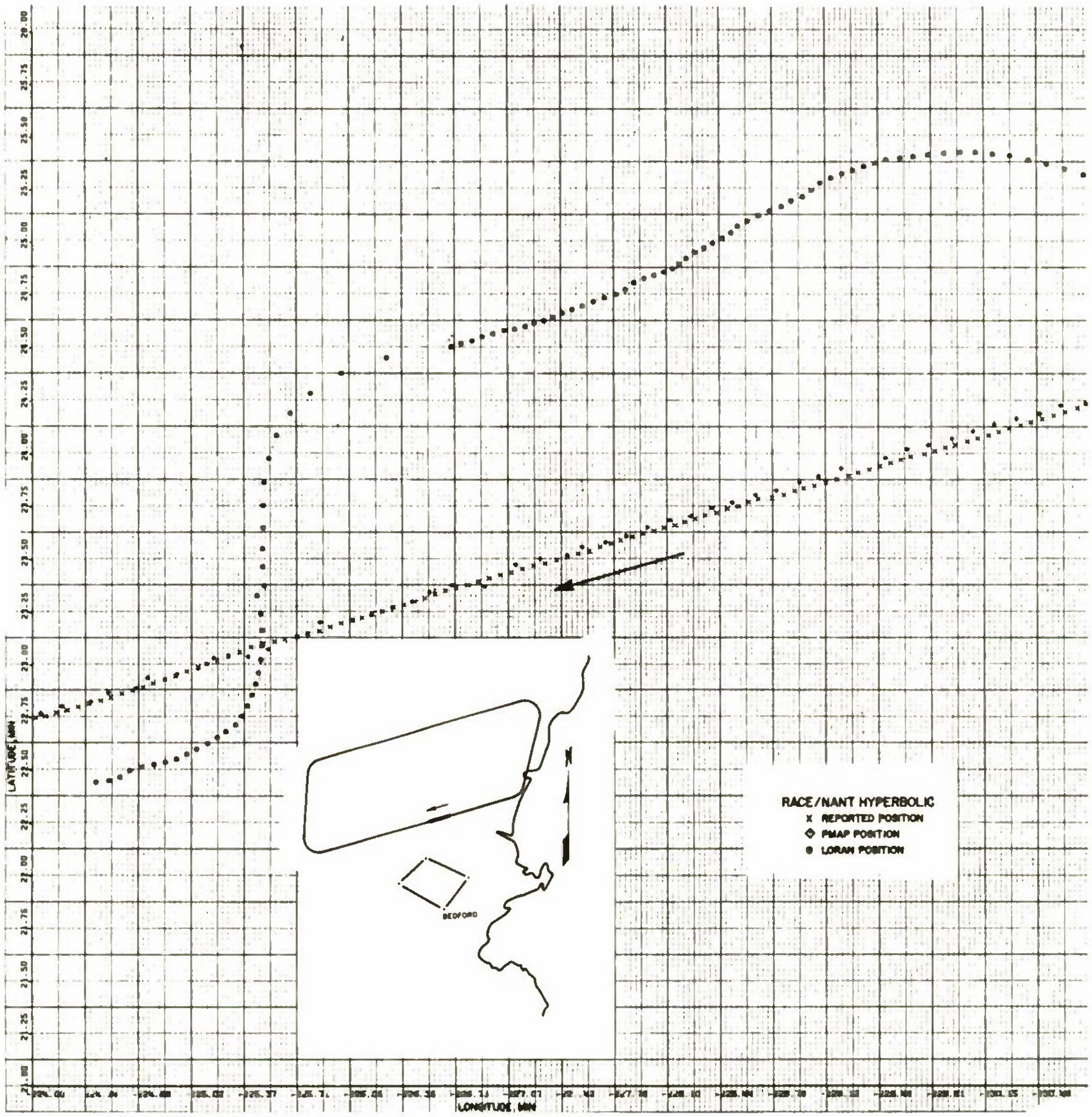

Figure 17 - Loran C Error Caused by Incorrect Cycle Identification.

SECTION III

SUMMARY OF TEST RESULTS

The Teledyne Loran-C receiver chosen for this test program has phase lock loop time constants selected to allow operation in high performance aircraft without external velocity aid. This receiver, operating in the Loran-C signal environment of New England, produces a one-shot or single fix relative position accuracy of from $\pm$ 250 feet (3σ) in direct ranging mode to $\pm$ 800 feet (3σ) in hyperbolic mode using Nantucket and Dana and $\pm$ 420 feet (3σ) in direct ranging to $\pm$ 650 feet (3σ) in hyperbolic using Cape Race and Dana.

The noise in the time difference data generating these position errors is dominated by very low frequency components with periods of 20 to 200 seconds. Long term (weeks) repeatable accuracy which is a function of chain stability and propagation changes was not specifically tested as pre-flight calibration is normal in the flight test procedure.

Calibration of Loran-C position at one point in the testbed area was found to produce relative bias accuracy throughout the test flight path of roughly the same as the repeatable accuracy when calibrated for Cape Race and Nantucket; however, a severe grid warp in the Dana time difference LOP's was discovered. Over the full flight path, this produced bias errors of 750 to 4000 feet relative to the calibration point. This normally undesirable situation is, in fact, a serendipity in view of the overall objectives of this program. We have, within the testbed area, both a Loran-C grid registered (after calibration) with the TDMA data link grid and a warped or unregistered Loran-C grid. These two situations will be exploited in the flight tests of the Kalman filter combination navigation system.